

**Title: Testing Spatial Correlation of Subduction Interplate  
Coupling and Forearc Morpho-Tectonics**

NASA project NAG5-11404

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**Project Description**

Subduction zones that are capable of generating great ( $M_w > 8$ ) earthquakes appear to have a common assemblage of forearc morphologic elements. Although details vary, each have (from the trench landward), an accretionary prism, outer arc high, outer forearc basin, an inner forearc basin, and volcanic arc. This pattern is common in spite of great variation in forearc architecture. Because interseismic strain is known to be associated with a locked seismogenic plate interface, we infer that this common forearc morphology is related, in an unknown way, to the process of interseismic strain accumulation and release in great earthquakes. To date, however, no clear relationship between the subduction process and the common elements of upper plate form has emerged. Whereas certain elements of the system, i.e. the outer arc high, are reasonably well-understood in a structural context, there is little understanding of the structural or topographic evolution of the other key elements like the inner arc and inner forearc basin, particularly with respect to the coupled zone of earthquake generation.

This project developed a model of the seismologic, topographic, and uplift/denudation linkages between forearc topography and the subduction system by: 1) comparing geophysical, geodetic, and topographic data from subduction margins that generate large earthquakes; 2) using existing GPS, seismicity, and other data to model the relationship between seismic cycles involving a locked interface and upper-plate topographic development; and 3) using new GPS data and a range-scale topographic, uplift, and denudation analysis of the presently aseismic Cascadia margin to constrain topographic/plate coupling relationships at this poorly understood margin. The SRTM

topographic data provided the impetus for this study. These data present an unprecedented opportunity to use globally-distributed, uniform topographic data to investigate a fundamental tectonic process that creates and modifies earth surface topography. Our hope is that the generalized model will enable the use of topography as a first-order tool for identifying and characterizing the key great earthquake-generating reach of subduction zone interfaces. Analysis of the morphology of the Cascadia Coast Range is a major focus of this study because: 1) Cascadia is now known to have generated great earthquakes (Mw 8-9); 2) The down-dip extent of the zone of interseismic strain accumulation is poorly constrained; 3) There have been no instrumental plate-boundary earthquakes to evaluate seismic coupling and hazard; 4) The forearc morphology is strikingly similar to other forearcs; and 5) New GPS measurements suggest the locked zone may extend beneath the Coast Range (the inner arc high). Because seismic potential and hazards in Cascadia are so great, this forearc is of particular interest to extend lessons learned from comparison of other subduction systems. This study will likely provide important new data for natural hazards related to both earthquakes and denudation at Cascadia and other subduction margins.

## Research Objectives

The processes and permanent evidence of deformation in subduction zone forearcs is poorly known. In some cases, we have a glimpse of the result of many seismic cycles from the pattern of uplifted marine terraces. In other cases, even this sparse information is absent or unavailable. GPS velocity fields clearly indicate that forearcs undergo deformation. However, the relationship between elastic and inelastic forearc deformation is elusive. Subduction zones have a suite of well-known characteristic topographic elements (we use the term 'topography' to refer to the subaerial and submarine regions between the volcanic arc and trench), particularly those that generate great earthquakes. The seaward forearc, usually comprising an accretionary wedge, is built by inelastic processes for the most part. Arcward of the accretionary prism, most subduction zones have an outer arc-high, and an adjacent forearc basin(s). Further landward, a "coastal range" and a second forearc basin commonly are found just trenchward of the volcanic arc. At present, neither the origins of these first-order elements, their relationship to subduction processes, nor the variability between subduction zones are well understood. Early forearc models described forearc structural features (e.g. Dickinson and Seely, 1979), and later investigations into great earthquakes have largely focussed on subducting plate age, differences in plate coupling, and convergence rate, without much inclusion of structural geology and morphology. This perhaps to be expected, as great earthquakes are the realm of the seismologist to a great extent. Today, seismicity, geodetic, geophysical, and geologic data are increasingly available for most subduction zones around the globe, and can now be integrated into cross-disciplinary investigations. For a number of subduction zones, we have a first order understanding of where the coupled plate interface lies, based on tsunami models, deformation models based on GPS and other geodetic data, and seismicity. The coming availability of a global high-resolution topographic dataset provides a unique opportunity, when coupled with geologic and geophysical data, to analyze quantitatively the morphologic characteristics of great-earthquake generating subduction zone systems globally. Such an analysis will likely provide a test of the earlier models, a new understanding of the form of subduction plate boundaries as they relate to the seismic cycle, the long-term accommodation of plate interaction, and the fundamental mechanical elements of the plate interface.

During this project, we performed an integrated analysis of forearc topographic data utilizing the high-resolution SRTM digital topographic data. These data provide a global and relatively uniform dataset of interferometric terrain data, as well as radar data that are capable of imaging landforms through vegetation canopy. In order to take advantage of the unique globally-uniform characteristic of the SRTM data, we focused on six subduction zones for which similar

geologic, geophysical, and geodetic data are available (Nankai trough (Japan), Gulf of Alaska, Sumatra, Makran, and southern Chile, and central America). Key we addressed include:

- 1) Where are the regions of interplate coupling and earthquake generation in relation the principal forearc topographic elements?
- 2) Are those first-order forearc topographic elements linked characteristically to the seismogenic zone specifically?
- 3) How does along-strike topographic variation relate to segment boundaries on the subduction interface, upper plate bedrock lithology, patterns of denudation, and/or characteristics of the down-going plate?
- 4) Does morphologic analysis provide a predictive framework for understanding downdip changes in the mechanical behavior of the plate interface?
- 5) Can forearc topography and interseismic strain patterns be used to better understand the occurrence and position "seismic gaps", areas with little historic seismicity, and the dimensions of coupled zones?

We developed general models of forearc morphology as they relates to documented seismicity, tsunami generation, and seismic cycle landform change. We then compared these regions with lesser known areas such as Cascadia (US) where evidence of Holocene earthquakes is abundant, but the location of the locked interface poorly defined. For Cascadia in particular, we used a two-pronged approach. Part of the effort focused on a detailed investigation into the origin and deformation of the Coast Range as a function of long-term rates and patterns of uplift and erosion using the SRTM data as a foundation. Combining a global comparative analysis of subduction systems with investigation of the form and modern deformation at Cascadia, a less well-constrained margin, has led to insight into potential signals in forearc topography arising from the subduction process, insight into how that form relates to the seismogenic interface, and has provided new constraints on the deformation and seismogenic potential associated with Cascadia in particular.

## Results

For Cascadia, the lessons gleaned from other subduction zones can be applied to the issues of plate coupling and seismic hazards along the Cascadia forearc. At the Cascadia subduction zone, the landward extent of plate coupling can not be seen directly in interplate earthquakes, as is possible at other subduction zones. Coastal uplift rates estimated by Mitchell et al. (1994) and Hyndman and Wang (1995) can be interpreted with a variety of coupling models (see also McCaffrey 2000). Moreover, the uplift rates are tied to a tectonic reference frame only weakly through tide gauges, raising additional doubt as to their usefulness for constraining coupling. GPS data provide a less ambiguous method for understanding the full extent of plate coupling. Preliminary indications are that the transition zone extends further landward than the thermal modeling of Hyndman and Wang predict (1995), extending to or east of the Oregon coast range (Goldfinger et al., 1998; McCaffrey et al., 2000)

. GPS results also show a margin-parallel strain gradient consistent with a downdip termination of the coupled zone at or east of the coast range. If the plates were in fact coupled only offshore, then the margin-parallel shear strain should be occurring offshore or in the western Coast Ranges. The GPS vectors in the Oregon forearc reveal a pattern that is similar to that observed in NW Sumatra, where clear strain partitioning occurs. The coastal sites show a large NE motion but at an angle relative to the coast which is more oblique than the plate convergence

vector. Despite the apparent scatter in the GPS vectors, the average contractional strain direction is nearly parallel to the convergence vector, giving us added confidence in the GPS results. The small deflection of the contraction direction from the plate convergence direction suggests that the strain is partitioned and that the margin-parallel shear strain occurs on the east side of our network. Our contraction direction agrees with that estimated by Murray and Lisowski (1998) based on older geodetic data but our contractional strain rate of about 0.07 microstrain/yr (this is a velocity difference of 7 mm/yr over 100 km distance) rate is roughly 75% faster. Similar results have now been reported from the northern Cascadia forearc of Washington and Vancouver Island (Miller et al., 1998; McCaffrey et al., 2000; Dragert et al., 1998)

The new GPS data provide a less ambiguous means of estimating locked zone position than previously available. Applying a standard elastic model to the Cascadia data suggests that to a first order, the transition zone extends approximately to the eastern margin of the coast range. Alternatively, a non-linear transition from full coupling to free slip can also satisfy the data.

### **Morphologic Correlations**

Correlations between the spatial position of the principal morpho-tectonic features of the forearc and the underlying locked zone were investigated using GIS techniques for the Cascadia, Aleutian/Alaska, Central America, Southern Chile, Makran, Nankai, and Sumatra subduction zones. Spatial associations were examined with the spatio-analytical tools of the ARCGIS Geographic Information System (GIS), and seismic and geodetic data were integrated with NASA Shuttle Radar Topography high-resolution digital topographic data. Correlations between forearc morpho-tectonics and subduction interplate coupling via integration of primary geophysical observations and digital topographic data were successful in that common morphologic elements were found to correspond to the known or modeled position of strong interplate coupling in most cases. These results strongly suggest a genetic connection between interplate coupling and ubiquitous forearc topographic elements. This result provides insight into potential for great earthquake generation within the seven studied subduction zones, and may offer potential to apply these methods to subduction zones that are less data rich.

### **Topography, uplift rates, and stream incision in Cascadia**

Relationships between concavity, rock type and rock uplift rate in the Cascadia forearc were examined to independently unravel the contribution of along-strike variations in lithology and rates of vertical deformation to the topographic relief of the Oregon Coastal Range. Lithologic control on river profile form is reflected by convexities and knickpoints in a number of longitudinal profiles and by general trends of concavity as a function of lithology. Volcanic and sedimentary rocks are the principal rock types underlying the northern Oregon Coast Ranges (between 46° 30' - 45° N) where mixed bedrock-alluvial channels predominate. Average concavity in this region is = 0.57. In the alluviated central Oregon Coast Ranges (between 45° - 44° N) values of concavity are, on average, the highest (= 0.82). South of 44° N, however, bedrock channels predominate and = 0.73. Mixed bedrock-alluvial channels characterize rivers in the Klamath Mountains (from 43°N south; = 0.64). Rock uplift rates of 0.5 mm/yr, mixed bedrock-alluvial channels, and concavities between = 0.53-0.70 occur within the northernmost Coast Ranges and Klamath Mountains. Concavities for rivers flowing over volcanic rocks are = 0.53 and = 0.72 for reaches crossing sedimentary rocks. Whereas channel type and concavity generally co-vary with lithology, rivers between 44.5° and 43° N do not follow these trends. Concavities are generally greater than 0.70, alluvial channels are common, and river profiles lack knickpoints in this central region; despite the fact the lithology is invariant. Moreover, rock uplift rates in this region vary from low, 0.5 mm/yr, to subsidence (<0 mm/yr). These observations are consistent with models of transient river response to a decrease in uplift rate. Conversely, the

ivers in the southern Oregon Coast Ranges have similar concavities and flow on the same bedrock unit as the central range, but have bedrock channels and irregular longitudinal profiles, which suggests the river profiles reflect a transient response to an increase in uplift rate. If correct, these results indicate the Oregon coastal mountains are unlikely to be in steady state between rock uplift and erosion, indicating that the topographic variability is a result of differential uplift rates, reflecting the underlying subduction tectonics. A similar topographic signal is recently been observed along the Sumatra-Andaman subduction zone, where aftershocks of the MW9.3 December 26<sup>th</sup> 2004 earthquake are concentrated along the forearc ridge where it is in high relief. Low relief areas are relatively free of aftershocks. We expect our Cascadia results, highlighted by the recent earthquake and aftershocks, are yielding good information about forearc topography and its origins in subduction settings.

### **Student Training and Education**

This grant supported two MS theses by Grant D. Kaye and Sam VanLaningham. These were completed in 2003.

### **Publications resulting from this grant**

- Kaye, G. D., 2003, Testing spatial correlation of subduction interplate coupling and forearc morpho-tectonics [MS thesis]: Oregon State University, 106 p. One CD-ROM containing GIS datasets from seven subduction zones.
- Kaye, G. D., Goldfinger, C., and Meigs, A. J., 2003, Testing spatial correlation of interplate coupling and forearc morpho-tectonics; a new model for comparative subductology based on high resolution digital elevation data: Geological Society of America, Cordilleran Section, 99th annual meeting, v. 35, no. 4, p. 32.
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